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by Henry W. Brandhorst, Jr., and Earle O. Boyer

Lewis Research Center

Cleveland, Ohio

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SUMMARY

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An airplane was used to carry solar cells to various heights ranging from 12, 000 to 47, 000 feet. Air masses above the cells then ranged from 0. 14 to 1. 2, depending on the altitude and the time of year. Semilogarithmic plots of the short-circuit current against air mass proved to be linear within experimental error as predicted by theory. Extrapolation of the plots to air mass zero yielded short-circuit currents equivalent to outer-space short-circuit currents, except for a correction for absorption of sunlight by ozone. This correction factor could be calculated with sufficient accuracy and was about 1 percent. In addition to the ozone correction, the results were normalized to a solar intensity of one solar constant (139. 6 mw/sq cm), and when necessary, to a standard temperature. In order to determine the absolute accuracy of the method, standard solar cells calibrated for outer-space conditions by a variety of techniques were flown. For cells calibrated on a Bell Telephone Laboratory solar simulator, the agreement was within ±1 percent. For cells calibrated in terrestrial sunlight on Table Mountain, California, the correlation was again within ±1 percent. The final tests were made with secondary standards prepared by careful comparison and matching of cells with a balloon-flown primary standard solar cell. In this case, agreement was within 0. 5 percent. These results indicate that it is feasible to use high-altitude aircraft to obtain outer-space short-circuit currents of solar cells to an accuracy of ±1 percent or better.

Author

INTRODUCTION

At the present time, there are two techniques that utilize sunlight to obtain the outer-space short-circuit current of solar cells. The first, which has been studied extensively by the Boeing Company (private communication from H. Oman) and the Jet Propulsion Laboratory (ref. 1), uses balloons to reach altitudes in excess of 75, 000 feet. While the balloon is at its maximum altitude, short-circuit currents of the cells on board are measured and telemetered to the ground station. At the conclusion of the experiment,

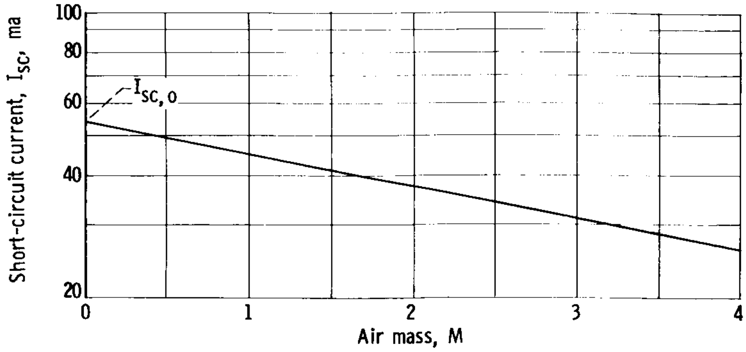


Figure 1. - Theoretical Langley plot of typical silicon solar cell.

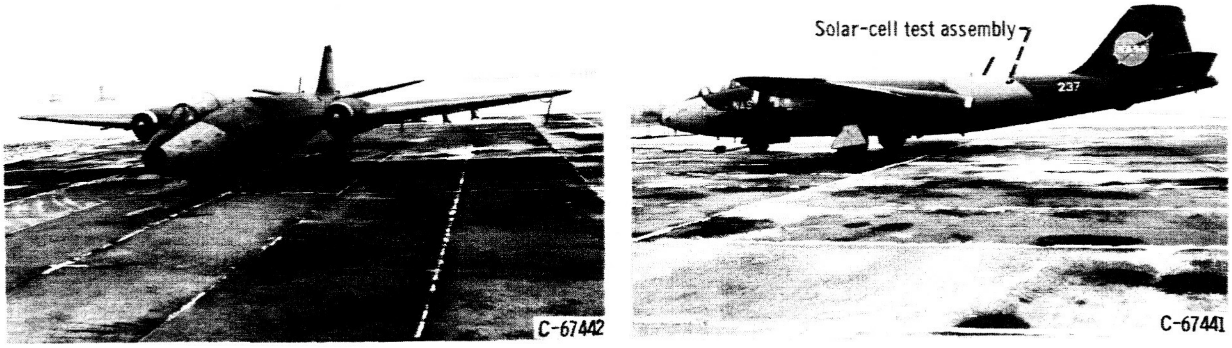
the cells are parachuted to Earth and later recovered.

A second method, originated by J. A. Zoutendyk (ref. 2) makes use of a Langley-type plot. In this technique, short-circuit currents are measured throughout the day at Table Mountain, California, (34°22' N., 117°41' W., altitude, 7400 ft) and then plotted logarithmically as a function of air mass. Extrapolation to air mass zero yields the outer-space short-circuit current. Air mass is simply a measure of the amount of atmosphere through which the sunlight passes. Air mass 1 is defined as being that quantity of air between a sea-level observer and the Sun when the Sun is directly overhead. Air mass 2 occurs when the Sun is at an elevation angle of 30° above the horizon, again at sea-level conditions. At altitudes above sea level, this geometric factor must be multiplied by the ratio of the ambient pressure to standard sea-level pressure to adjust for pressure differences. Thus, as the altitude increases, the pressure ratio approaches zero, and hence the air mass approaches zero also. The air mass M can then be defined in terms of the solar elevation angle H_c and the ambient pressure P in atmospheres as

$$M = P \sec (90^\circ - H_c)$$

The geometric portion of the equation involving $\sec (90^\circ - H_c)$ is exact only at solar elevation angles larger than about 30°.

In order to test the linearity of the Langley plot for solar cells, short-circuit currents for a typical solar cell were calculated as a function of air mass. The results are plotted in figure 1, which shows that the plot of the logarithm of short-circuit current against air mass is a straight line out to air mass 3. Balloons can reach air masses of 0.03 and below; hence, they can practically reach outer space. On Table Mountain, an air mass as low as 0.8 can be obtained. Extrapolation of a Table Mountain Langley plot to air mass zero, however, can be suspect for several reasons: First, small errors made at large air masses can drastically change the value of the outer-space short-circuit current because the extrapolation is a long one (the last point at air mass 0.8 is



(a) Front view. (b) Side view.

Figure 2. - B-57B used in solar-cell testing program.

still some 20 percent below the desired value at air mass zero). Second, days on which the atmosphere remains unchanged for many hours are infrequent, and thus the measurement is complicated. The accuracy of the Langley plot technique could be greatly increased by using high altitude aircraft to fill in the gap below air mass 1.

The use of an airplane to obtain outer-space short-circuit currents through use of a Langley plot has several additional advantages. First, the airplane is most certainly above ground haze and low-lying atmospheric disturbances. Second, instrument errors on any one point do not appreciably affect the extrapolated value of the outer-space short-circuit current. Third, the airplane is a convenient, versatile, and stable system.

A motion-picture film supplement has been prepared and is available on loan. A request card and a description of the film are given at the back of the report.

EQUIPMENT

The airplane, chosen because of its performance as well as its availability, is the B-57B (fig. 2). It is a twin-jet aircraft with a crew of two, a pilot and a research observer. Experimental equipment can be installed in several locations in this airplane. Electronic recording equipment is placed in the cockpit where it is convenient to the observer and is in a controlled environment. The pyrheliometer and collimating tube assembly containing the solar cells are mounted in the tail section as shown in figure 3 (p. 4). There is no window over these units because this area is not pressurized. Both items are mounted in a frame that can be pivoted from 20° to 75° in elevation so as to correspond to the position of the Sun during the flight. The pivot point is located at the top of the frame, close to the skin of the aircraft, so that the size of the cutout in the

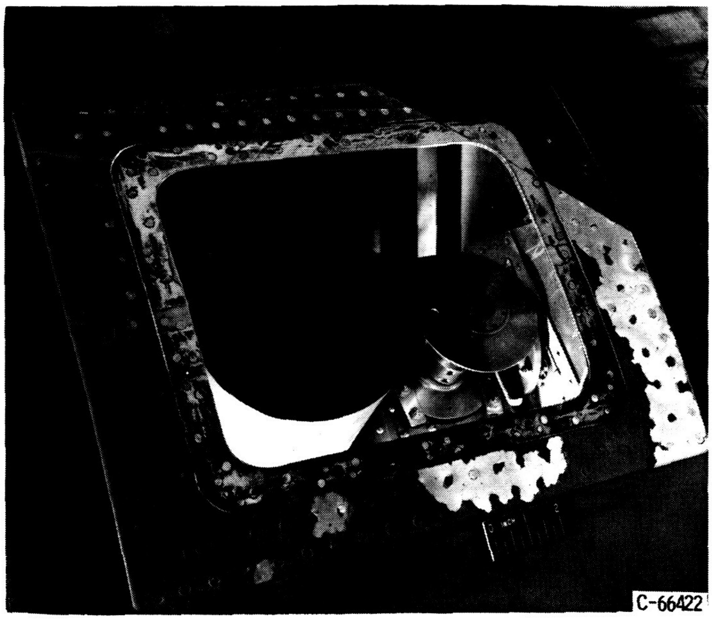


Figure 3. - External view of pyrheliometer and collimating tube.

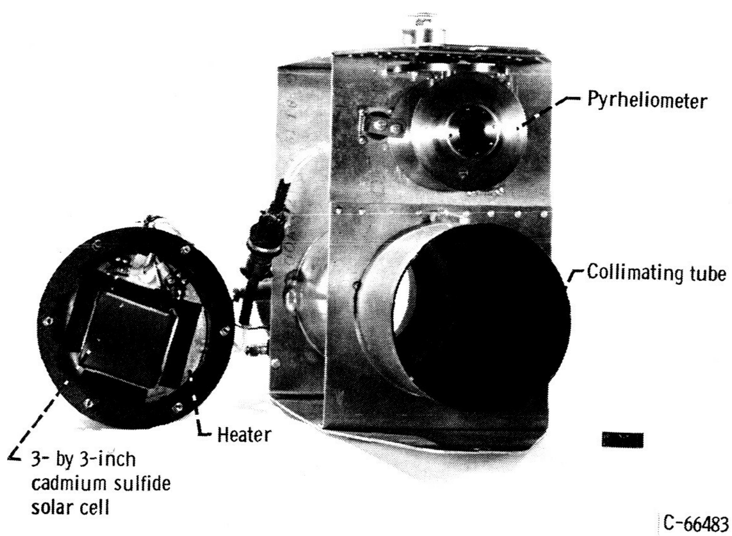


Figure 4. - Detail of collimating tube assembly.

airframe is minimized.

Because there is no window over these units, the cells are exposed to a harsh environment with ambient temperatures as low as -50° C. Therefore, the cells are mounted on a thermostatically controlled heater. The entire assembly is pictured in figure 4. A 3- by 3-inch cadmium sulfide cell is mounted on the heater. The average temperature attained by the cells depends on the type of mounting used. For various cell holders, temperatures between 15° and 30° C have been obtained. It should be stressed that, for any given mounting, a variation of less than 4° C from the average temperature is observed during the run. These sample temperatures are measured two ways: first,

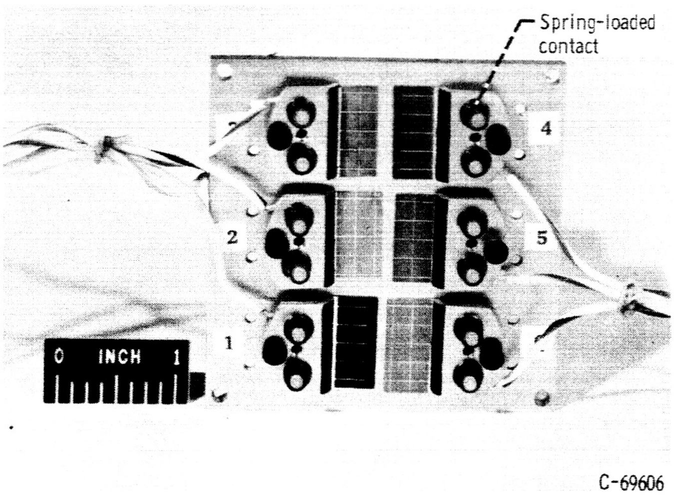


Figure 5. - Sample holder for conventional solar cells.

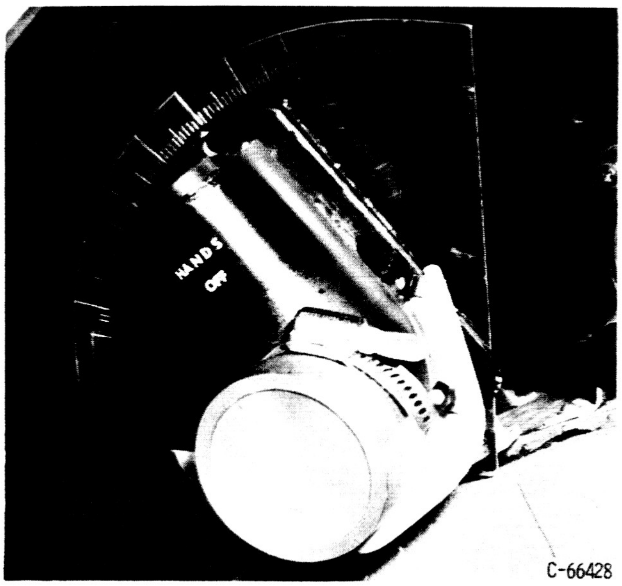


Figure 6. - Pilot sight tube.

a thermistor is attached directly to the sample holder; second, and more important, the open-circuit voltage of one cell is recorded. Temperatures measured by both methods change by less than 4° C during any one run.

Figure 5 shows the sample holder used for flying conventional solar cells. It is 3 inches square and can accommodate six cells with dimensions to 2 by 2 centimeters. The contacts are spring loaded, and the unit is gold plated to minimize contact resistance. Consistency of the results is assured by using one cell as a monitor and flying it every time. The open-circuit voltage of this cell is also used for temperature indication.

The short-circuit currents are measured as voltages across a 1-ohm load. For a normal silicon cell, the current measured in this way is essentially a true short-circuit current because of the flatness of the I-V characteristic in this region. This is not the case, however, for a 3- by 3-inch cadmium sulfide solar cell, and additional ground measurements have to be made to obtain the true short-circuit current in this case. The resistor used is accurate to 0.1 percent and has a temperature coefficient of 20 parts per million per $^{\circ}$C.

The collimating tube was designed so that even with a 2° variation in pitch, roll, or yaw complete illumination would be maintained over a $4\frac{1}{4}$-inch-diameter circle. This ensures that a 3-inch-square area will be under constant illumination. The angle of the tube is chosen to correspond to the elevation of the Sun at the time of the flight. Once the airplane is airborne, proper orientation of the tube to the Sun is assured by using an optical sight that is exactly parallel to the tube in the rear section (fig. 6). Periodic ground calibrations confirm this parallelism. A limit circle of 2° radius is inscribed on the face of the sight, and the Sun image is centered and maintained within this circle by the pilot.

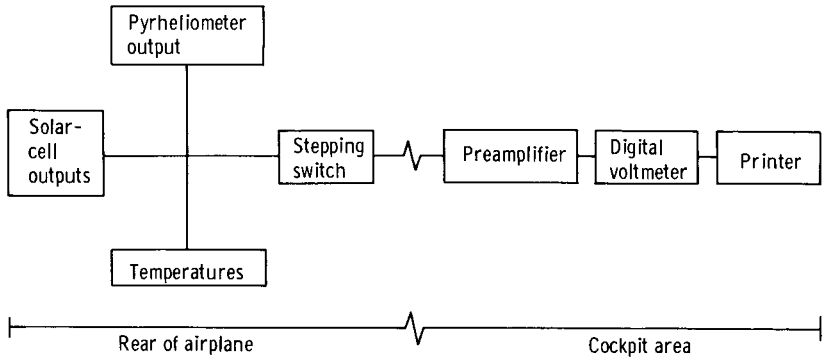


Figure 7. - Block diagram of data acquisition system.

The pyrheliometer is a normal incidence instrument that has been temperature compensated. This unit serves as a monitor of the solar intensity. The pyrheliometer was shock mounted in two axes with plate-type mounts that provided equal spring rates in all directions. Because of extreme temperature range encountered in these flights, a silicone base elastomer was chosen to provide maximum protection. The temperature of this unit is also recorded during the flight.

A block diagram of the data acquisition system can be seen in figure 7. For a typical run with six solar cells, there will be six short-circuit currents, one open-circuit voltage, the temperatures of the mounting and the pyrheliometer, and the output from the pyrheliometer. The 10 voltages are sequentially indexed through the stepping switch. All readings are voltages; hence, a recording digital-voltmeter system was chosen to collect the data.

The recording digital-voltmeter system is composed of three units: the four-place digital voltmeter, a printer-scanner with a capacity of 20 channels of information, and a preamplifier with a maximum gain of 1000. The first two units are located beside the observer, while the preamplifier is mounted in a separate compartment because of space requirements. Two problems were encountered with the operation of the preamplifier. First, because the signals vary over three orders of magnitude, several gain changes are required during the run. Because the preamplifier cannot be manually operated by the observer, these gain changes are performed remotely by the stepping switch for each individual reading. Second, temperatures as low as -15° C have been observed at the preamplifier during test flights; therefore, the preamplifier is wrapped in heating blankets that are controlled by the observer. It was observed that 400-cycle noise was being introduced into the preamplifier input from the aircraft 115-volt, 400-cycle power supply. This created instability of operation at preamplifier gains of 100 and 1000. Input filtering did not appreciably help, so the electric blankets are now shut off just before a run and are then turned on again at its conclusion. This sequence is repeated at each altitude.

Proper synchronization between the printer and the stepping switch is indicated by a light controlled by the stepping switch. If a discrepancy is observed, the stepping switch

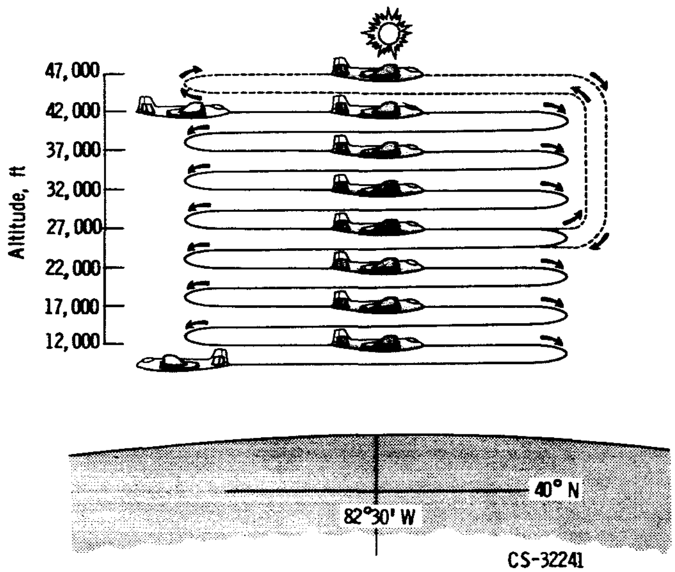


Figure 8. - Typical flight pattern for B-57B solar-cell testing flights.

can be manually advanced by the observer without affecting the rest of the system. A signal light is also provided to indicate operational status of the preamplifier.

EXPERIMENTAL PROCEDURE

The tube angle is computed from the 1964 air almanac (ref. 3) or the 1964 nautical almanac (ref. 4) and the Sight Reduction Tables (ref. 5). The time chosen for this calculation is approximately 11:30 true solar time so as to experience a minimum variation of the Sun angle during the flight. For example, the solar elevation of May 20, 1964, for 1700 Greenwich mean time at 40° north latitude and $82^{\circ}30'$ west longitude can be calculated as follows:

$$\text{Declination } (\delta) = 19^{\circ}53'$$
$$\text{Greenwich hour angle} = 75^{\circ}54'$$
$$\text{Local hour angle} = \text{Greenwich hour angle} - 82^{\circ}30'$$
$$= 353^{\circ}24'$$

Then, from the Sight Reduction Tables (ref. 5), the solar elevation angle H_c is $69^{\circ}06'$.

It should also be noted that the maximum solar elevation for this day is $69^{\circ}53'$. Because these flights generally take place from 11:30 to 12:30 solar time, it can be seen that only minor corrections are normally required by the pilot to ensure proper tube alignment.

Figure 8 shows the pattern used in these flights. The area, chosen for its convenience, is at 40° north latitude and $82^{\circ}30'$ west longitude, which is just east of Columbus, Ohio. The airplane enters the flight pattern at 42,000 feet and is flown on a heading approximately 90° to the azimuth of the Sun. The pilot then centers the Sun image in the sight and stabilizes the craft. (A discussion of the technique used by the pilot to achieve and maintain this attitude is included in the appendix.) Once the plane is on course and stable, the observer initiates the print sequence, and at least four repetitions of the data are recorded. Time and altitude are also noted. Again, the time of the flights is chosen close to solar noon to ensure both minimum air mass and minimum change in elevation of the Sun. All altitudes are based on a pressure altimeter that is set relative to sea-level pressure. After data are taken at the 42,000-foot point, the airplane descends to 37,000 feet and the sequence is repeated. The descent continues in 5000-foot intervals until the 27,000-foot sequence is completed. If data are to be obtained at 47,000 feet, the flight plan follows the alternate route. This measurement is not made sooner because the quantity of fuel on board severely limits the rate of climb of the airplane. Data are then taken at 22,000 feet, and the series is continued to 12,000 feet, weather permitting.

DATA REDUCTION

After the flight, the air masses are computed as follows. The position of the Sun can be calculated for any time of day by the method outlined earlier. Thus, for a local time of 12:23 e.s.t. on May 20, 1964, this calculation gives a solar elevation of $69^{\circ}52'$. This method of calculation is rather time consuming and can be shortened considerably in the following manner (ref. 6). At a local time of 12:23 e.s.t., the local mean solar time is

$$\begin{aligned}\text{Local mean solar time} &= 12{:}23 - (4\ \text{min/deg})(82^{\circ}30' - 75^{\circ}) \\ &= 11{:}53\end{aligned}$$

The true solar time is

$$\begin{aligned}\text{True solar time} &= \text{Local mean solar time} + \text{equation of time} \\ &= 11{:}53 + 00{:}03{:}34 \\ &= 11{:}56{:}34\end{aligned}$$

It should be noted that the calculation of local mean solar time is simplified since all flights occur at $82^{\circ}30'$ west longitude and thus the correction is always 30 minutes.

By reference to a graph of the solar elevation for the different declinations as a function of true solar time, the solar elevation is graphically determined to be $69^{\circ}50'$; this closely approximates the value previously calculated. These graphs may be obtained from data given in table 170 of the 1958 Smithsonian Meteorological Tables (ref. 6) or they can be computed directly by using the detailed calculation. Because of the accuracy necessary in this study, the latter method was chosen for the construction of the graphs. The errors incurred in this graphical technique are well within the plotting accuracy of the Langley plot.

Once the elevation has been determined, the geometrical portion of the air mass can be calculated. For high solar elevations, this geometric factor is accurately represented by the secant of the angle of the Sun from the zenith. An elevation angle of 30° above the horizon corresponds to a zenith angle of 60°, hence to a geometric factor of 2 ($\sec 60^{\circ} = 2.00$). Values of the geometric factor m for all solar elevations can be found in table 137 of the 1958 Smithsonian Meteorological Tables or computed directly from the secant of the solar zenith angle.

Values of atmospheric pressure are obtained from the pressure altitude and values given in the U. S. Standard Atmosphere, 1962 (ref. 7). The aircraft altimeter is accurate to within 75 feet and is always set to read relative to sea-level pressure (29. 92 in.). This allows direct reference to the standard atmosphere table.

Typical values of the air masses encountered in this work are as follows: With the Sun at its maximum elevation (in June) and the airplane at an altitude of 47, 000 feet, a minimum air mass of 0. 14 is obtained. Conversely, with the airplane at 12, 000 feet and the Sun at its lowest point over the test area (in January), the air mass is about 1. 4. Of course, both of these conditions cannot be met in one flight, so the practical range lies from 0. 14 to 0. 67 in June and from 0. 3 to 1. 4 in January.

An example of the calculation of the complete Langley plot is given in table I (p. 10). At each altitude there are four values of the short-circuit current. The solar elevation was determined by the graphical technique. The weather was extremely clear for this flight so a data point was measured at 7, 000 feet in place of one at 47, 000 feet.

The Langley plot of these data is shown in figure 9 (p. 11). The best straight line fit of the data was made. The expected linear relation is observed with an air mass zero intercept of 54. 0 milliamperes. Three corrections must be applied to the recorded data to obtain the true value of the outer-space short-circuit current:

(1) Correction for the distance from the Earth to the Sun, which changes the value of the solar intensity reaching the Earth

(2) Resistance change of standard resistors due to low ambient temperatures

(3) Correction for the nonuniform distribution of ozone in the atmosphere

The first correction is necessary because the absolute value of the solar intensity reaching the Earth varies throughout the year because of the eccentricity of the Earth's orbit about the Sun. The absolute value may range from 144. 3 to 135. 0 milliwatts per square centimeter. The value of the solar constant at the mean Earth-Sun distance (1 AU) is 139. 6 milliwatts per square centimeter. The solar intensity $\mathcal{J}$ can be calculated for any time of the year by using an inverse-square-law correction as follows:

$$\mathcal{J} = \frac{139.6}{R^2} \text{ mw/cm}^2$$

where R is the Earth-Sun distance in astronomical units as given in The American

TABLE I. - TYPICAL FLIGHT DATA AND CALCULATIONS

[Date, May 20, 1964.]

	Altitude, ft							
	42,000	37,000	31,000	27,000	21,600	16,600	11,600	6,600
Short-circuit current, I_{sc}, ma	52.9	52.4	51.8	51.9	51.3	50.7	49.4	48.2
	52.9	52.6	51.9	51.9	51.0	50.4	50.0	48.2
	53.0	52.3	51.8	51.5	51.1	50.5	49.3	48.9
	53.0	52.3	52.4	51.5	51.2	50.3	49.9	48.9
Average short-circuit current, $I_{sc,av}$, ma	53.0	52.4	52.0	51.2	51.7	50.5	49.6	48.6
Time (e.s.t.)	12:23	12:33	12:44	12:55	13:07	13:16	13:24	13:32
Solar elevation angle, H_c, deg	69.9	69.7	69.5	68.9	68.0	67.4	66.5	65.3
Geometric factor, m, sec (90^o-H_c)	1.065	1.066	1.068	1.072	1.078	1.083	1.090	1.101
Pressure, P, atm	0.169	0.214	0.284	0.340	0.430	0.529	0.646	0.783
Air mass, M, P sec (90^o-H_c)	0.180	0.228	0.303	0.364	0.464	0.573	0.704	0.862

Calculation

The radius vector R is

$$R = 1.01198 \text{ AU}$$

and

$$R^2 = 1.024$$

The solar intensity $\mathcal{J}$ is then

$$\mathcal{J} = 136.3 \text{ mw/sq cm}$$

Ephemeris and National Almanac (ref. 8) (1 AU = 149.6×10^6 km). All calculations are normalized to 139.6 milliwatts per square centimeter so as to correspond to an average condition. For this example, $R^2 = 1.024$ and $\mathcal{J} = 136.3$ milliwatts per square centimeter. Therefore, the extrapolated short-circuit current must be increased by 2.4 percent to normalize the reading to 139.6 milliwatts per square centimeter at 1 astronomical unit.

Second, a 0.1-percent correction must be added to correct for the resistance

TABLE II. - CALCULATION OF OZONE ABSORPTION CORRECTION

Wavelength interval, μ	Fraction of solar-cell response, $\Delta S/S$	Fractional decrease in solar intensity caused by ozone absorption, $\Delta\mathcal{J}/\mathcal{J}$	Fraction of short-circuit current, $\Delta I_{sc}/I_{sc}$
Silicon n/p cells			
0.30 - 0.40	0.022	-----	------
.41 - .50	.080	0.005	0.0004
.51 - .60	.139	.046	.0064
.61 - .70	.170	.021	.0036
.71 - .80	.187	-----	------
.81 - .90	.192	-----	------
.91 - 1.00	.161	-----	------
1.01 - 1.20	.049	-----	------
	1.000		[a]0.0104
Gallium arsenide cells			
0.30 - 0.40	0.002	-----	------
.41 - .50	.057	0.005	0.0003
.51 - .60	.151	.046	.0070
.61 - .70	.238	.021	.0050
.71 - .80	.327	-----	------
.81 - .90	.225	-----	------
.91 - 1.00	------	-----	------
1.01 - 1.20	------	-----	------
	1.000		[b]0.0123

[a]Correction = $(\Delta I_{sc}/I_{sc})$(fraction of ozone above test area) = (0.0104)(0.9) = 0.009 = 0.9 percent.

[b]Correction = (0.0123)(0.9) = 0.011 = 1.1 percent.

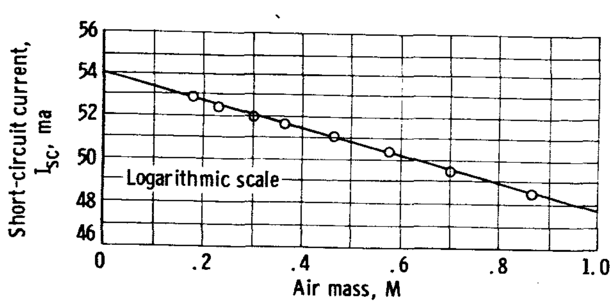


Figure 9. - Langley plot of p/n silicon cell.

change of the standard resistors due to their average temperature of about -20° C.

The third correction must be made because of the nonuniform distribution of ozone in the atmosphere. About 80 percent of the ozone is still above 47,000 feet. While the major ozone absorption occurs in the ultraviolet region below the response of most solar cells, there is a weak absorption in the visible region between 0.4 and 0.7 micron known as the Chappuis band. Because this absorption is within the normal response range of solar cells, the decrease in the short-circuit current of the cell from this source must be computed.

This correction was calculated by multiplying the fraction of solar-cell response $\Delta S/S$ in the appropriate wavelength intervals by the fractional decrease in the solar intensity $\Delta\mathcal{J}/\mathcal{J}$ caused by ozone absorption in the same intervals. Ozone absorption coefficients determined by Vigroux (ref. 9) were used. The value so obtained was then multiplied by the average amount of ozone still above the test area. The ozone distribution given by Biryukova (ref. 10) was assumed in this calculation.

Typical corrections for a n/p silicon cell and a gallium arsenide cell are shown in table II. Corrections for cadmium sulfide cells were about 1.2 percent.

The cell characterized in figure 9 is a p/n silicon cell and has a slightly

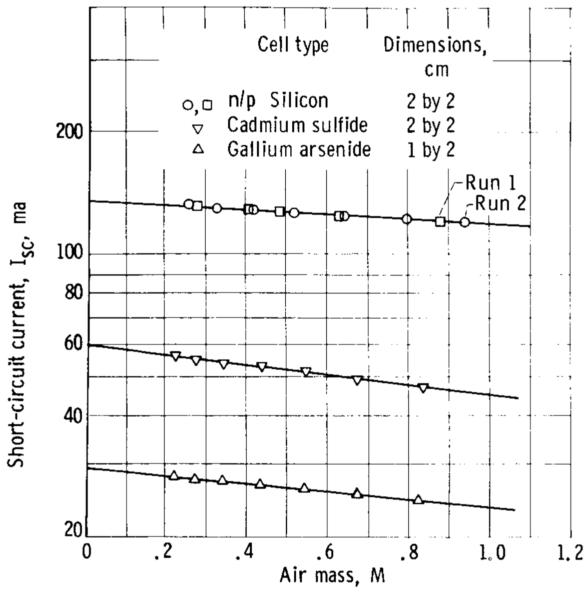


Figure 10. - Typical Langley plots for various types of cells.

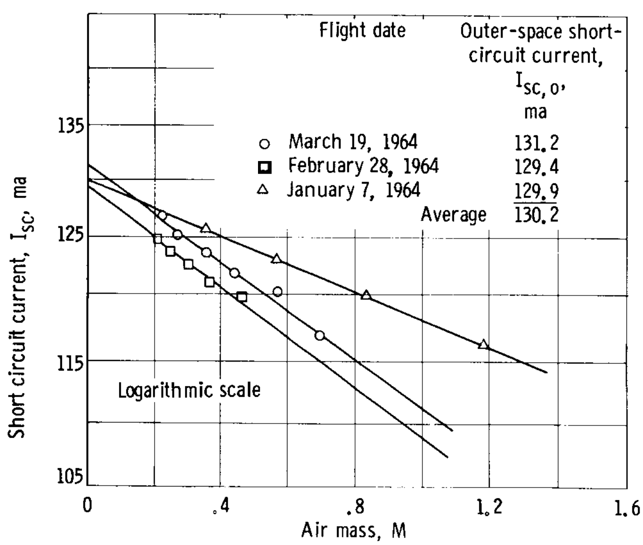


Figure 11. - Reproducibility of aircraft system.

different correction factor of 0.8 percent. The total correction to be added to the extrapolated outer-space short-circuit current $I_{sc,o}$ is 3.3 percent (solar intensity, +2.4 percent; temperature of resistors, +0.1 percent; ozone, +0.8 percent). Thus the corrected outer-space short-circuit current is 55.8 milliamperes. The average temperature of the cell during the run was $16^{\circ} \pm 4^{\circ}$ C. From a knowledge of the temperature coefficient of the short-circuit current in sunlight, an $I_{sc,o}$ value can be obtained for any operating temperature desired.

RESULTS

Figure 10 shows the Langley plots obtained for three additional types of solar cells: a n/p silicon cell, a gallium arsenide cell, and a cadmium sulfide cell. In all cases, the expected linear behavior is observed. The data for the silicon cell are from two runs. All the previously mentioned corrections have been applied to these data, so the extrapolated values represent true $I_{sc,o}$ values.

An example of the reproducibility of this system is demonstrated in figure 11. This cell was flown over a period of 3 months from January to March. All values of the outer-space short-circuit current agree to within ±1 percent even though the slopes are sometimes different. The low slope is apparently caused by the nonconstancy of the atmosphere and its constituents and has been observed on about 25 percent of the flights.

For calibration purposes, a number of silicon solar cells that had been measured on the ground were flown. These cells were obtained from the Bell Telephone Laboratory and had been calibrated on the solar simulator there. This calibration was confirmed by measuring these cells on the modifed Bell simulator at Lewis at the time of the

TABLE III. - COMPARISON OF AIRPLANE CALIBRATION OF SILICON SOLAR CELLS WITH OTHER TECHNIQUES

Cell	Solar-cell outer-space short-circuit current, $I_{sc,o}$, ma							
	Airplane				Modified Bell simulator	Carbon arc 1	Carbon arc 2	Table Mountain (a)
460	57.7	58.1	58.2	58.6	58.7	61.0	60.9	59.2
454	55.1	54.7	54.7	54.8	54.8	56.9	56.0	55.0
469	58.5	58.5	----	----	57.0	60.5	60.3	59.0
471	57.7	----	----	----	57.2	59.4	59.7	57.8
443	56.7	----	----	----	57.0	58.5	56.9	56.9

[a](I_{sc} at 100 mw/sq cm)(1.17).

flights. The results of these flights are shown in table III. For the sake of uniformity, a monitor cell was flown on every flight. These test cells had also been measured on two carbon-arc simulators and at Table Mountain, California. A factor of 1.17 was used to convert the Table Mountain readings to outer-space values. This factor was obtained at the time the cells were measured at Table Mountain. Excellent agreement of the Table Mountain results with the airplane data is obtained. Also, agreement between the airplane and the modified Bell simulator results is generally within 1 percent, while the carbon-arc results seem to be about 3 percent higher than the airplane results. As can be seen from the data on cells 460 and 454, the reproducibility of the system is again within ±1 percent.

MEASUREMENTS ON SECONDARY STANDARD CELLS

The first comparison of balloon-flown and airplane-flown cells was made by Hadley (ref. 11). Three cells that had been calibrated in the airplane were taken to Table Mountain and checked against a balloon-flown cell. The accuracy of this latter calibration is not better than ±1 percent. After the data were normalized to 139.6 milliwatts per square centimeter, deviations of -1.7 to -3.2 percent, averaging -2.4 percent, were observed between the airplane and the balloon calibrations. Unfortunately, the airplane data had not been corrected for losses due to ozone and the temperature dependence of the short-circuit current. When these corrections were applied to the data, deviations of -0.2 to -1.7 percent, averaging -0.9 percent, were obtained. This is within the accuracy of the combined techniques. It was felt necessary, however, to check the system further by using a standard cell that had been calibrated under very carefully controlled conditions.

The details of the method of calibration of secondary standard solar cells have been described elsewhere (ref. 12) and will be briefly summarized here. A group of solar cells were mounted in the standard American Institute of Electrical Engineers holder and were compared against a primary balloon standard cell in terrestrial sunlight at

TABLE IV. - COMPARISON OF CALIBRATION METHODS FOR NASA STANDARD CELL 182

Temperature correction factor, airplane	Solar-cell outer-space short-circuit current, $I_{sc,o}$, ma		
	Airplane value	Corrected airplane value	Balloon value primary calibration
1.0030	[a]48.2	[b]48.3	[c]48.45

[a]Cell temperature, $24^{\circ}\pm2^{\circ}$ C.

[b]Cell temperature, 28° C.

[c]Calibration value at solar intensity of 139.6 mw/sq cm and cell temperature of 28° C.

Table Mountain. The spectral response of the primary standard closely matched those of the test cells. The cells were mounted on an equatorial tracker which ensured normal incidence of the sunlight, and the temperature of the cells was maintained at 28° C. At least 64 data points were measured for each cell and correlated with the nearly simultaneous measurement of the primary balloon standard. A balloon flight of two cells calibrated in this way verified the accuracy of the method.

NASA standard cell 182 was flown in the airplane on July 31, 1964 and on August 5, 1964. The regular monitor cell was flown as a check of the system as usual. On both flights, deviation of the monitor cell from its calibrated value was no more than 0.1 milliampere or 0.2 percent. The average cell temperature was $24^{\circ}\pm2^{\circ}$ C, and the temperature coefficient of NASA standard cell 182 was 0.075 percent per $^{\circ}$C. For both flights, the extrapolated value of the short-circuit current was 48.2 milliamperes after correction for ozone and adjusting the intensity to 139.6 milliwatts per square centimeter. Table IV summarizes these results and compares them to the primary calibration against a balloon-flown cell. Both values are taken at 28° C and 139.6 milliwatts per square centimeter. Primary calibration data for NASA standard cell 182 were taken from reference 12 and have an accuracy of ±0.9 percent. The agreement shown in table IV is excellent and confirms the accuracy of the airplane technique for calibrating solar cells.

SUMMARY OF RESULTS

An investigation using a high-altitude aircraft (a B-57B) to calibrate solar cells showed that such an airplane is a stable and convenient system for this purpose. Linear Langley plots for various types of solar cells were obtained for air masses between 0.14 and 1.2. In order to determine the absolute accuracy of the system, standard solar cells calibrated by a variety of techniques were flown. For cells calibrated on a Bell Telephone Laboratory simulator, the agreement was within ±1 percent. For cells calibrated in terrestrial sunlight on Table Mountain, by using a suitable factor derived at the time of measurement, the correlation was again within ±1 percent. The final calibration was made with cells that had been compared directly with balloon-flown cells.

For cells in which the initial calibration conditions were very carefully controlled and spectral responses were closely matched to the balloon standard cell, the agreement was within 0.5 percent. These results indicate that it is feasible to use high-altitude aircraft to obtain the outer-space short-circuit current of solar cells and that the consistency of such calibrations is at least ±1 percent.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 19, 1964.

APPENDIX - FLIGHT OPERATIONS

A major requirement of the airplane solar-cell test facility is that enough data can be collected in one flight to establish an accurate plot of log I_{sc} against air mass. Such a mission profile requires a flight of approximately 2 hours and 30 minutes of which 1 hour and 15 minutes is on-station time t. To compensate for variables exisiting within the on-station time requirements, such as solar elevation angle H_c and aircraft flight attitudes, optimization of the profile is desirable.

The Sun reaches maximum elevation at 12:00 true solar time. Since t just exceeds 1 hour, data collection should begin at approximately 11:30 true solar time. This results in minimum net change in H_c. Furthermore, it is desirable to compute H_c for $T + \frac{1}{4}t$, where T is the true solar time when data collection is to begin. Delaying or advancing takeoff by 30 minutes can result in H_c variations in excess of 4°. In north latitudes this factor is not as critical during periods of south declinations.

Figure 12 shows angle of attack α of the aircraft as a function of speed and gross weight. Figure 12 shows that the aircraft must be flown at some positive angle of attack above approximately 30,000 feet because of design-speed limitations. Below this altitude such high speeds are required that longitudinal control is very sensitive. It is therefore desirable to use slower speeds to obtain a positive angle of attack throughout the typical profile flown. It is convenient to fly the B-57B at an angle of attack α of 1.5° to 40,000 feet, 2° to 45,000 feet, and 3° to 50,000 feet. For example, from figure 12, for 36,000 pounds gross weight at 37,000 feet, the aircraft limit speed is

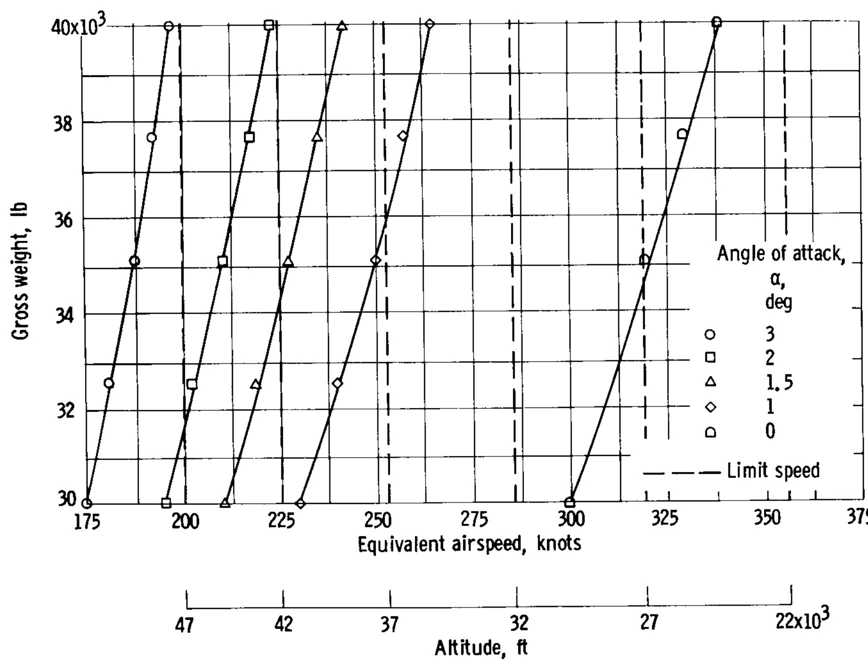


Figure 12. - Aircraft angle of attack as a function of gross weight and equivalent airspeed.

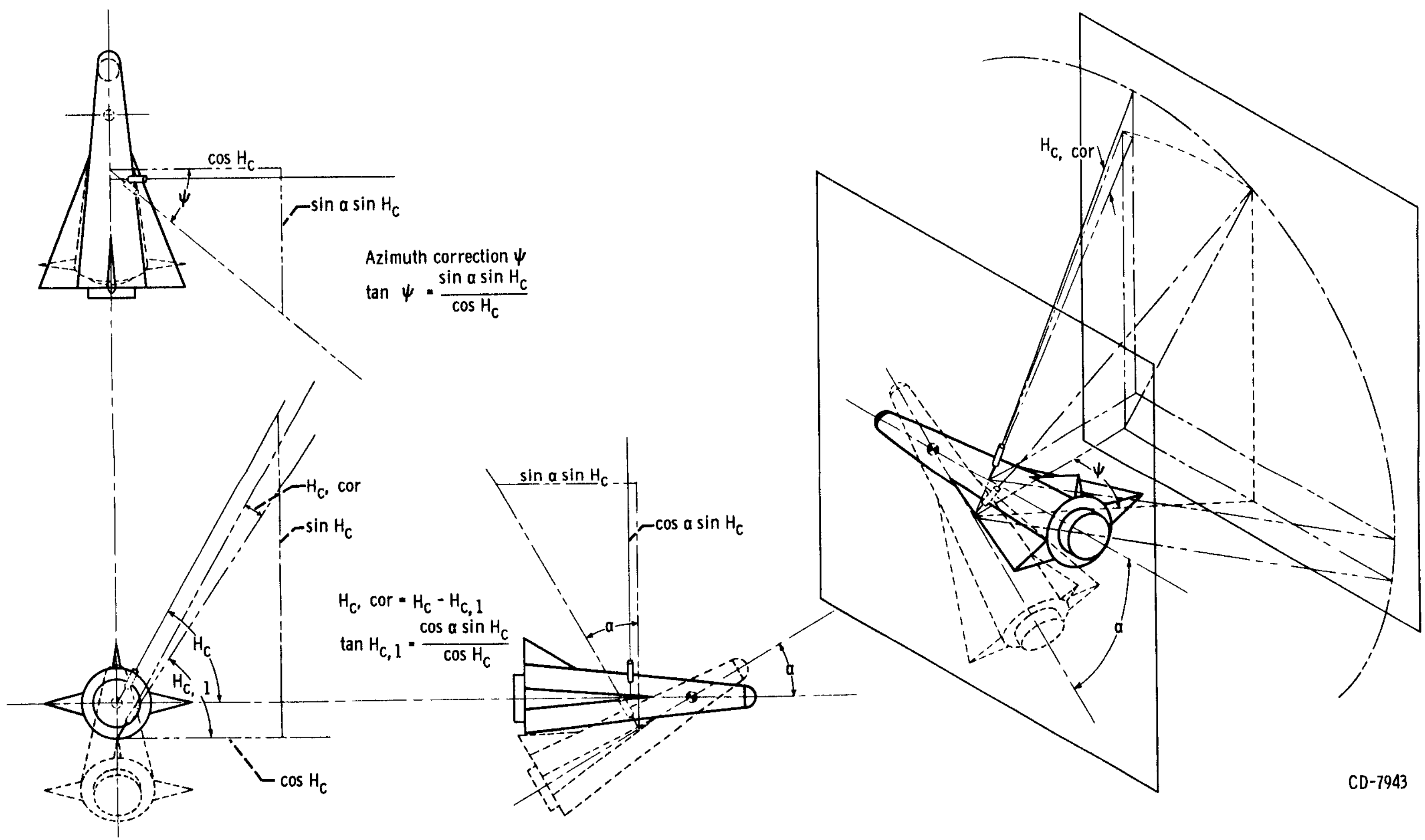


Figure 13. - Solar cell correction angle geometry.

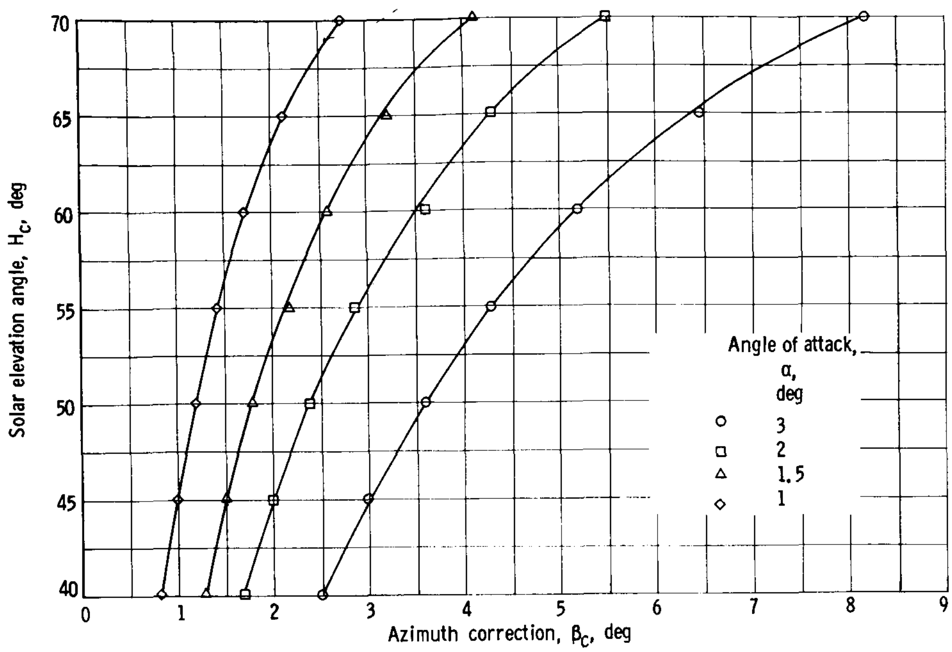


Figure 14. - Azimuth correction for typical solar-cell mission.

approximately 253 knots equivalent airspeed. This speed would result in an angle of attack slightly less than 1°.

The solar-cell collimating tube, located aft of the aircraft center of gravity, is displaced in a counterclockwise motion with an increase in α above 0°, as shown in figure 13. Thus a correction must be made in elevation H_c and azimuth to realign the tube to the computed values.

The azimuth correction ψ may be expressed as

$$\tan \psi = \frac{\sin \alpha \sin H_c}{\cos H_c}$$

Corrections up to 8° are realized for a typical solar-cell mission, as shown in figure 14. When α is positive, the elevation correction $H_{c,cor}$ may be expressed as

$$H_{c,cor} = H_c - H_{c,1}$$

where

$$\tan H_{c,1} = \frac{\cos \alpha \sin H_c}{\cos H_c}$$

This results in a minor correction between approximately 0° and 15', which can easily be eliminated by a minor sideslip.

From the previous discussion it can be seen that, at any gross weight, the angle of attack can be controlled by flying at the proper equivalent airspeed. Then, with the solar-elevation angle known, the azimuth correction can be found and applied to the computed azimuth.

Practice has shown that with proper Sun-spotter interpretation the pilot can search for the correct azimuth and maintain the cell colliminating tube perpendicular to the Sun's rays within 1°.

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